Water

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Summary

Water use of forests in the Netherlands

Introduction

This thesis analyses the water use of five different forest types in the Netherlands. The main question leading to the present PhD thesis was: "What is the difference in water use between different tree species in the Netherlands?". This question was divided into the following three underlying research questions:

- "What are the main processes controlling the magnitude of the different components of the water balance of forested areas in the Netherlands?";
- "What are the controlling parameters of these processes and are they related to tree species?";
- "Will this knowledge be of added value to predict effects of different tree species on the water balance?".

Theory of forest evaporation

Evaporation is arguably the component of the water balance with the highest uncertainty. To improve on this uncertainty the main focus of this study is on the processes that govern the evaporation rate of forests. Two main conditions are distinguished: the evaporation from a wet canopy and the evaporation from a dry canopy. As the controls of the evaporation rate are different for these conditions, they are discussed in separate chapters: Chapter 7 "Dry canopy evaporation" and Chapter 8 "Wet canopy evaporation". The theory and equations governing the water and energy flow of a forested plot are introduced in Chapter 2 "Theory of forest evaporation". The theory and equations provide the basis for the parametrizations of a numerical model. In the subsequent Chapters, the concepts behind these equations

are evaluated to determine possible conceptual improvements to simulate the effects of land-use changes on the water balance.

Characteristics of the research sites

For this thesis an extensive amount of data has been collected at five different forest sites in the Netherlands, i.e. Bankenbos, Edesebos, Fleditebos, Kampina and Loobos (see Fig. 3.1). A detailed description including most of the parameters representing the characteristics of the vegetation and the soil at these sites is provided in Chapter 3. Table UK.1 provides an overview of the forest characteristics at the different sites.

The two forest stands with the most pronounced differences in their site characteristics are the Loobos site with a stand of *pine* trees on sand soil and the Fleditebos site with a stand of *poplar* trees on a clay soil. The differences in soil type together with the low groundwater table at Loobos and the relatively high groundwater table at Fleditebos also create large variety in hydrological conditions between these two sites.

The differences in maximum total L_{AI} between the sites is mainly based both on the differences between broad leaved and needle leaved tree species (see Table 3.16) and on the timing of the peaks in L_{AI} of the undergrowth and the trees (see e.g. Fig. 3.13). Both at the Fleditebos site as well as at the Loobos site the L_{AI} of the undergrowth reached almost the same maximum L_{AI} (m^2 m^{-2}) as the trees at the specific sites. The largest variation in total L_{AI} was found for the *poplar* stand at the Fleditebos site, while the *larch* stand at the Bankenbos site showed the least amount of variation in L_{AI}.

Comparison of the groundwater table depths with the rooting depths at the different sites (see Fig. 3.24), shows that deep groundwater tables coincide with deep rooting depths and vice versa.

If the water holding capacity W at the start of a drought is defined as the difference in soil water content at a pressure $\psi = -10^{2.1}$ Pa (i.e. pF 2.1) and $\psi = -10^{4.2}$ Pa (i.e. pF 4.2), Table 3.16 shows that, except for the Loobos site, the amount of soil water easily extractable for evaporation is 87.8 mm on average. If it is assumed that there is no additional soil water available by lateral or vertical transport, the maximum amount of soil water available for evaporation is greatest at the *mixed forest* stand of the Kampina site. Even with the deepest roots of all sites, the maximum amount of available soil water at the *pine* stand of the Loobos site is very low, i.e. 20.8 mm. This low amount of available soil water implies that in principle the vegetation at the Loobos site is most prone to water stress, especially if the roots are not close to the groundwater table.

Table UK.1: *Vegetation characteristics near the observation towers at the sites. All values are average values for the stand. If available, the standard deviation is given between brackets. The tree heights z_{tree} are given at the start as well as at the end of the observation period. All other characteristics have been averaged over this observation period.*

	Bankenbos	Edesebos	Fleditebos	Kampina	Loobos
Tree species	Larch	Oak	Poplar	Mixed deciduous and coniferous	Scots pine
Undergrowth	Purple moor grass	Bare soil and some regrowth of oak	Stinging nettle, cleavers and grass	Purple moor grass	Grass
Planting date		1944	1985	1890,1930	1904
Observation period	1995-1997	1988-1989	1995-1998	1996-1998	1995-1998
Tree density (tree ha^{-1})	300	600	440	310	403
Tree height (m)	22.0-23.4 (1.5)	17.1-17.4 (n.a.)	16.2-18.7 (0.5)	16.6-17.0 (4.1)	15.3-15.7 (2.0)
DBH (m)	0.29 (0.04)	n.a.	0.24 (0.02)	0.26 (0.12)	0.25 (0.05)
Projected crown area (m^2 tree^{-1})	35 (11)	n.a.	20 (4)	40 (28)	21 (10)
Crown base (m)	14.7 (1.5)	n.a.	8.7 (0.8)	7.1 (3.8)	9.5 (1.6)
L_{AI} tree (-) max.	1.8	4.9	3.7	3.8	1.9
Canopy cover fraction (-) max./min.	0.6/0.4	0.69/0.2	0.8/0.2	0.95/0.45	0.7/0.55
L_{AI} under (-) max.	-	-	4	1.3	1.5

Hydro-meteorological measurements at the sites

All sites, except for the *oak* stand at Edesebos had the same general set-up with some minor differences depending on the specific site. This set-up is discussed in Chapter 4 and consisted of a scaffolding tower with an extendable mast mounted at the top. On top of this mast a 3D sonic anemometer and a Krypton hygrometer were mounted. These were used to derive the latent and sensible heat fluxes using eddy correlation techniques. To measure the carbon flux, at the *pine* stand the inlet of an infra-red gas-analyser was added next to the hygrometer in 1996. In 2000 this closed path system and hygrometer were replaced by an open path sensor measuring water vapour and carbon dioxide. An automatic weather station measuring wind speed, wind direction, temperature, humidity, incoming and outgoing long and short wave radiation was set up on the scaffolding tower. Here, also a tipping bucket rain gauge was mounted. In addition there was a tipping bucket installed in an open space nearby. Under the canopy the throughfall was measured using 36 manual gauges as well as a tipping bucket rain gauge at the end of an approximately 10 meter long trough. Stemflow was measured from 6 trees on a weekly basis. The soil heat flux was measured using 4 flux plates in combination with 2 temperature/soil moisture profiles. All data were stored at 30 minute intervals, except for the tipping bucket rain gauges for which a 5 minute interval was used.

At the Edesebos site in the *oak* stand a Bowen ratio system was used instead of an eddy correlation system. The Bowen ratio was measured using the Thermometer Interchange System. Most of the other measurements were set-up similar to those at the other sites.

In 1997 two special campaigns for a duration of several months were held. During these campaigns additional measurements were made below the canopy of the *poplar* stand and of the *pine* stand. For this an eddy-correlation system was set-up similarly to the one used above the canopy and in combination with measurements of air temperature, humidity and net radiation.

The data used for this thesis concern the years 1988, 1989 for the *oak* stand at the Edesebos site and the years 1995, 1996, 1997 and 1998 for the other sites. The longest time series used are the data from 1995 to 2009 of the *pine* stand at the Loobos site.

Quality control of the flux measurements

As the fetch conditions of the site determine the location and the magnitude of the contribution of the sources upwind of the flux sensor an estimation is made of the length of the fetch. The length of the fetch together with the quality assessment of the measurements are discussed in Chapter 5.

After storing all data in a database a quality check was performed (see Fig. 6.1). Flags were used to distinguish between time slots with missing data, data accepted as good data and data of questionable quality. The accepted data were then used to derive relations between different variables. Based on these relationships synthetic data were produced.

The data marked as questionable were compared with the synthetic data, checked for consistency in the time series and their quality check flags were checked. The original measurement was accepted if it complied to three conditions:

- Firstly, the measured data did not cause any inconsistency in the time series.

- Secondly, the synthetic and measured data did not differ much.
- Thirdly, the reason(s) the flag(s) were set could be considered as a warning instead of an error.

If the data did not comply to these conditions, the measurement was qualified as unreliable and the data were rejected.

Analysis of the fetch conditions (see Table 5.1) shows that for the major wind direction at all sites the origin of the maximum flux is well within the footprint area of the towers. The Loobos site and the Fleditebos site may be considered most homogeneous for all wind directions.

From the comparison with the full rotation corrections it followed, that the influence of the omission of the rotations on λE is negligible, i.e. well below 5%.

The relatively good closure of the energy balance based on daily values (see Fig. 5.3), as well as the good resemblance of the measured and modelled co-spectra of $\overline{w'\varkappa'}$ (see Fig. 5.2) give confidence to the quality of λE. The fact that the closure of the energy balance for 30 minute data is less good, i.e. $> 80\%$, indicates that a large part of the uncertainty is in the estimates of the heat storage in both the soil and biomass.

If closure of the energy balance is used as an estimate of the uncertainty of the measurement, λE derived in this study using an eddy-correlation system is in summer time better than 5% and in winter time better than 15% for the Bankenbos, Fleditebos and Loobos sites. For the Kampina site the percentage of energy balance closure in summer time is less good, i.e. the uncertainty is better than 15%.

The uncertainty in λE when using a Bowen ratio system is estimated for day time values on a clear day in summer as 10%, and for a dry day in spring with low humidity differences as 20%.

The analysis of the behaviour of the measured wind components with the sonic anemometer showed the little effect of rain on the performance of this sensor. Also the limited number of available data from the open path Krypton hygrometer at the Fleditebos site under wet conditions, showed a reasonably good closure of the energy balance i.e. better than 80% (see Fig. 5.6), as well as a reasonably good agreement with the modelled spectra (see Fig. 5.5).

These findings demonstrate the good performance of the sonic anemometer and hence the relatively good estimates of H under wet conditions. The associated uncertainty in λE based on the percentage of energy balance closure is better than 20%.

Gap filling to generate continuous datasets

Long term measurements rarely produce continuous records. Gaps in the data series may be caused by instrumental failure such as power breaks or because data are deemed to be of insufficient quality. However, continuous data sets are of paramount importance in modelling studies and interpreting measurements of different sites. Sometimes the data gaps in this study were biased towards certain meteorological conditions. For example a number of sensors tended to work less well under wet conditions. In the Netherlands wet conditions are in winter and summer often associated with specific wind directions. If this bias was not taken into account and relations derived for dry periods were used to replace missing data in wet periods, serious biases could be obtained.

To provide an unbiased method for filling data gaps, the capabilities of a neural network were explored in Chapter 6. Results showed that for data, such as temperature or specific humidity, gap filling could be much improved by including nodes representing the seasonal and diurnal cycle or by including measurements of the same variable measured by a different instrument at the same or at an other site. A distinct advantage of a neural network in gap filling is that it is not necessary to make assumptions about a physical relation between variables. For short time steps as used for this study, care should be exercised when only variables of different sites are used to feed the network. Because a neural network makes no assumptions about the physical relations between the variables the results are as good (or bad) as the data used to train the network.

Dry canopy evaporation

Chapter 7 describes the variation in parameter values determining the transpiration rate for five typical forests in the Netherlands and the contribution of the understorey for two of these forest stands. The main objective is to improve our understanding of the processes determining the transpiration rate of forest, with special attention to the differences between stands with different tree species and the contribution of the understorey. In view of the expected increasing frequency of periods of prolonged droughts, special attention is paid to the root water uptake and the parametrization of water stress. For the two sites with more abundant undergrowth an attempt is made to separate the evaporation rate of the understorey and the trees. To explain the variation in evaporation between years and between sites the Jarvis-Stewart parametrization using a sparse canopy single and dual source model is optimized for different periods.

The main driver for surface conductance g_s at all sites was vapour pressure deficit e_D. Although a parabolic response function was used for the temperature relationship of g_s, this relationship was not well established at the lower air temperature T_a range.

At lower temperatures i.e. below the optimum air temperature there was no clear reduction of g_s found for these sites at a mid latitude location. This behaviour may be caused by the fact that at lower T_a at these sites the dew on the undergrowth never completely disappeared.

This unclear relationship of g_s at lower T_a and the strong correlation between T_a and e_D for higher T_a makes the temperature relationship of g_s redundant.

Hence, in view of the limited variation between the sites, the parameter values for g_s as f(T_a) may be set to a fixed value. Based on the improved R^2 for almost all years at the different sites after setting $\mathrm{f}(T_a) = 1$, it is recommended to use $\mathrm{f}(T_a) = 1$ for all forests sites in the Netherlands.

The low sensitivity of the forests to θ_D shows that these forests are not very sensitive to the range of changes in soil water experienced during this study. Whether these forests are sensitive to more severe droughts cannot be concluded from the present data sets. The proposed soil water stress model including a separate soil water feedback from deep soil layers, worked well for the conditions of this study, but needs to be tested for more extreme dry conditions.

The important contribution of the undergrowth to total evaporation rate E_{Tot} has been demonstrated for 2 forest sites in The Netherlands, i.e. the *pine* forest with its undergrowth mainly consisting of grass at the Loobos site and the *poplar* forest with its undergrowth mixture of grass, nettle and cleavers at the Fleditebos site (see Fig. 7.12). The contribution of undergrowth evaporation to total evaporation varied at the *poplar* forest of the Fleditebos site between 0.25 and 1.0, and at the *pine* forest of the Loobos site between 0.10 and 0.20.

The results of the tree evaporation when applying the dual source model compared well (see Table 7.9) with the sapflow measurements at the Loobos site. The over-estimation of the simulated undergrowth evaporation E_{Low} was most likely because of the limited data set being used for the derivation of the parameter set of Table 7.8. Such datasets are still limited. More extensive datasets will help to decrease the uncertainty in the modelled undergrowth evaporation rate.

Wet canopy evaporation

Chapter 8 discusses the main parameters determining the amount of precipitation stored on the vegetation and subsequently evaporated. Attempts have been made to improve the estimates of wet evaporation E_i and canopy water storage C, two of the most important parameters to simulate interception loss.

Measurements show that both the roughness length for heat z_{0H} and for momentum z_{0M} are subject to changes under wet conditions. Use of a value for $kB^{-1} = 1.0$ to express the ratio between the aerodynamic resistance for heat and momentum (see Eq. 2.67) seems more appropriate for the *pine* forest of this study. The magnitude of kB^{-1} differs per site, is generally higher for the winter period, and is different for wet and dry periods. Only for relatively rare occasions kB^{-1} approached zero under wet conditions. These events were associated with large storms. Based on the data available for this study as a rule of thumb $kB^{-1} = 1.0 - 1.5$ may be used for needle leaf forests and $kB^{-1} = 3.0 - 4.0$ in summer and $kB^{-1} = 5.0 - 6.0$ in winter for broad leaf deciduous forests (see Table 8.1).

Estimates of the evaporation rate E during wet conditions based on regression analysis using measured throughfall T_f, stemflow S_f and precipitation P are approximately twice as high as E derived from the energy balance closure during showers. Possible causes for these differences are the systematic underestimation of measured P, but also the hourly data not taking into account the drip that occurs after the end of the time step. For event based data the use of measured T_f implicitly includes the amount of water left on the leaves at the end of the shower and thus also the relatively high E after the shower has ceased (see Fig. 8.4).

The fact that events without E are very rare or non-existent is the main cause for the often low values of C found when using techniques based on the method of Leyton et al. (1967). Using the sparse canopy model of Gash et al. (1995) and E derived from the energy balance closure to calculate C gives values 3 times higher as compared to using the method of Leyton. The largest differences occur especially during the winter months. The relatively good modelling results obtained with the Gash model using different parameter sets for the same location, exhibit the trade-off between C and E.

Fixed parameter values can decrease the model's daily performance considerably. For the Edesebos site this was mainly caused by differences in C.

Using site and tree specific kB^{-1} values in combination with C per unit canopy cover, will improve the general applicability of the interception models. The presented kB^{-1} and C values may well be used for similar forests under approximately the same conditions. More experimental data however will be needed to enable parametrization of the differences between sites, before the present results can be generally applied to regions with different climatic conditions.

Epilogue

To improve estimates of the actual evaporation of forests a five step approach is suggested in Chapter 9. An important part of this approach is the implementation of direct measurement of the actual evaporation rate at strategic sites for process understanding and verification purposes. Especially the real time use for verification is recommended during extreme conditions, such as droughts.

For future research related to the water use of forests there are two main challenges. The *first* is related to the increased risk of droughts and the effect of lowering groundwater tables on the physiology and water use of forests. The *second* research challenge is related to the still often ignored contribution of the undergrowth to the forest evaporation. To enable research in these directions, additional data sets will be needed. These data sets should especially aim at representing the different phenological phases of the vegetation and should include:

- Evaporation data sets of undergrowth,
- Evaporation and soil water data sets for forests under water stress.

Because of the strong link between transpiration and photosynthesis, the above mentioned challenges are also important for the research on the carbon exchange of forests.